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Trends in High Temperature Gas Turbine Materials

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Abstract

National technology efforts are underway to improve performance and durability of gas turbines for aerospace and terrestrial applications. High performance - high technology materials are among the technologies that are required to allow the fruition of such improvements. Materials trends in hot section components are reviewed, and materials for future use are identified. For combustors, airfoils, and disks, a common trend of using multiple material construction to permit advances in technology is identified.

Introduction

National technology efforts are underway on aircraft, space, and automotive turbines as well as on ground electric/industrial power turbines. In each case high temperature, high performance materials are the key to improved performance and optimum operation (Fig. 1). The maximum gas temperatures, design lives, and other important operational factors for some of these systems are summarized in Table 1.

The U.S. has long held a dominant position in world aircraft gas turbine engine markets. In order to maintain this position, a wide range of technology efforts are underway aimed at reducing fuel consumption as well as lowering maintenance costs and improving component durability. One such effort is the NASA Energy Efficient Engine (E^3) program. It has a goal of providing the technology to reduce fuel consumption of advanced commercial aircraft engines by at least 12 percent over that of current engines.[1] This is especially important since fuel costs have escalated rapidly in the last ten years and now represent about half of the airlines' direct operating costs. Such advanced engines will operate at temperatures over 1340° C (2450° F), similar to upgraded commercial engines, but will gain efficiency by operating at increased pressure ratios of about 36:1[2]. Under these operating conditions heat transfer rates will be significantly increased; thus, either materials temperatures will rise or improved cooling approaches will be required. In addition, higher stresses on airfoils and disks may also be expected. E^3 concepts involve segmented cast combustors, directionally solidified or single crystal blades, etc. If such advanced materials can also be incorporated into a turboprop engine system and if advanced composite propellers can be developed, the potential exists for a Mach 0.8 turboprop aircraft engine which may use 30 percent less fuel than the turbofan engines currently in the commercial fleet.[1] The primary aircraft turbine materials needs involve sustained strength at high temperatures, plus mission and service lives of critical parts extending to at least 9 000 hours.[3]

For Space Shuttle main engine turbopumps, again high performance, very high specific power, and reliability are mandatory. Due to the 100 mission reuse requirement, lives of at least ten hours are needed. The high pressure steam/hydrogen environment[4] causes very high heat transfer rates which result in extraordinary thermal fatigue demands.

Oil-fired gas turbines have become widely used by electric utilities to provide peaking power and by industry to provide back-up power in emergencies. In the utility area, attention has also been focused on fuel flexibility - developing hot-corrosion-resistant materials that allow these turbines to burn low cost residual oils containing vanadium, sulfur, etc. without catastrophic hot corrosion attack. Technology efforts now underway are aimed at extending the use of gas turbines to base-load service by combining them in "topping" cycles for steam boilers to improve electricity conversion efficiency.[5] Soon such "topping cycle" turbines will be fired on low Btu gas from coal. In this way hydrogen sulfide can be removed from the gas before turbine combustion allowing coal to be "burned" efficiently and in a more environmentally acceptable manner. In the future, technology efforts such as the Electric Power Research Institute's (EPRI) High-Reliability Gas Turbine Combined - Cycle Program[6] and DOE's (Department of Energy) High Temperature Turbine Technology (HTTT) Program may result in such turbines operating at inlet temperatures of ~1175°-1550° C, (2150°-2820° F) about the same or greater than aircraft gas turbines but for times to 50 000 hours. Here, for example, one approach proposes the use of water cooled airfoils,[7] turbine disks, etc. to maintain low metal temperatures so as to achieve long life. Therefore, materials are needed with both good aqueous and environmental corrosion resistance.

Similarly, technology attention has been given to pressurized fluidized bed coal combustors. Here coal mixed with limestone is "fluidized" and burns at ~900°-1000° C (1650°-1830° F). Very low thermal NO_x is thus generated. And, the oxides of sulfur formed during combustion react immediately with the limestone to form gypsum. The gas turbine in this concept ingests the hot bed gases (after most of the particulates have been removed in hot cyclones) and drives the compressor to pressurize the bed. The primary need is for corrosion/erosion resistant turbine materials operating at only the modest temperatures of ~700°-900° C, (1290°-1650° F) but again capable of 50 000 hours of uninterrupted service.[8]

For an automotive gas turbine, very low engine cost requirements, high performance, and fuel flexibility needs dictate hot uncooled turbines and thus ceramic materials for static and rotating parts. There are several DOE-funded efforts directed toward generating and verifying such ceramic technology. These include the DOE Automotive Gas Turbine Program (AGT) and the Ceramics for Advanced Turbine (trucks) Engines Program (CATE).[9,10] Such turbines will be designed for at least 3,500 hours of operation at turbine inlet temperatures to 1290° C (2350° F). Good progress is being made in both fabrication and ceramic materials technology for these applications.

Thus, higher temperature, higher strength, and more environmentally resistant materials appear to be needed for all gas turbine applications. The purpose of this paper is to examine the trends in high temperature materials development and to provide some insight as to what the future holds. Since the primary components that require high temperature materials are combustors, turbine airfoils, and disks, the material trends for these will be addressed.

Combustor Materials

In the past, combustor "cans" and annular combustors for aircraft gas turbines have been fabricated primarily of nickel-base alloys or stainless steel sheet materials. The need for complex shapes with holes and louvers for cooling air injection has mandated reasonable sheet ductility while good weldability was deemed important for structural assembly and repair. Current combustors have more holes, baffles, etc., but they still are made of ductile high temperature sheet materials. These trends in combustor materials are shown in Fig. 2.

Higher temperature nickel-base and cobalt-base sheet alloys as well as additional insulative oxide coatings are now serving to minimize local burnouts due to combustor hot streaks as well as to reduce thermal fatigue cracking and warpage. All of these factors contribute to improved component life. The cobalt-base alloys, however, have recently suffered from scarcity and price fluctuations, and the future may see a return to the nickel-base sheet materials.

The insulative oxide coatings - called thermal barrier coatings or TBCs - are shown schematically in Fig. 3. They will be discussed more fully in a later section of this paper. Here, however, it should be noted that the zirconium oxides now in use as the insulative layer in these coatings provide an additional benefit. They have low radiative absorptance and thus reflect thermal radiation from the burning gases. This results in lower heat fluxes to the combustor liner and further helps keep it cool. This factor is of growing importance for utility/industrial turbines which may have to operate on lower quality synethetic liquid fuels. Such fuels are expected to have lower hydrogen-to-carbon ratios resulting in more luminous flames.

Other advanced combustor liner concepts are also being developed. These involve the use of segments of highly-environmentally-resistant, oxide-dispersion-strengthened (ODS) iron alloys, such as Incoloy* MA956[11] attached to a more conventional nickel alloy structure. Since these ODS alloys can run hotter, they will need less cooling air and thus offer improved combustion efficiency. Due to the low strain to failure of the ODS materials, however, special design considerations must be given to their application. Several such ODS combustor design concepts are now being explored under the NASA-Materials for Advanced Turbine Engine (MATE) Program by Pratt and Whitney Aircraft. A film-cooled segmented-louver concept and a transpiration-cooled twin-wall concept are shown in Figs. 4(a) and (b), respectively. The E^3 program and DOE's HTTT programs are also developing the segmented combustor liner concept to reduce the thermal strains imposed on such structures.

In the Automotive Gas Turbine (AGT) Program, relatively simple ceramic combustor shapes are being designed to be slip cast of alpha silicon carbide. Current plans indicate that these combustors will be fabricated and tested at temperatures to 1300° C (2370° F) in the next year or two.

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*Trademark - International Nickel Co.

Turbine Airfoil Materials

The major trends in turbine blade materials is one of continuing increases in use temperature with time, as shown in Fig. 5. Early turbine blades were made of wrought alloys and were limited to use between 800°-900° C (1470°-1650° F). More complex gamma-prime-strengthened cast alloys allowed use temperatures to increase at a rate of about 5° C (9° F) per year. Then in the mid 1970's, macrostructural directionality was introduced in these castings and eventually single crystal turbine blade materials were developed. This macrostructural trend is depicted in Fig. 6 where design changes[12] plus directionality (Fig. 6-center) allowed the elimination of cooling (Fig. 6-left) without a reduction in inlet temperature. Single crystal blades (Fig. 6-right) will allow increases in operating temperature. Since single crystal materials are relatively new, their compositions can be expected to continue to improve with further effort.

Beyond these more or less conventionally cast alloys, slowly cooled eutectic compositions offer cast-in "fiber" reinforcement and higher use temperatures but the slow cooling rates required to maintain proper alignment of the reinforcing phase and the current compositional constraints must still be overcome. ODS superalloys will also provide additional strength as shown in Fig. 7. Attrition mixing and milling of superalloy and oxide powders followed by extrusion and directional recrystallization results in a material strengthened by the gamma prime phase at temperatures to about 900° C (1650° F) as in cast superalloys. The finely dispersed oxides help retain some strength even to temperatures of 1200° C (2190° F).[13] One such gamma-prime + ODS material is the alloy designated Inconel* MA6000. This material is also under development for turbine blade use in the NASA MATE program by the Garrett Turbine Engine Co. This material is similar to the Incoloy MA956 material previously discussed in the advanced combustor section. However, the MA6000 matrix is a face-centered-cubic nickel-base alloy rather than body-centered-cubic iron-base alloy in Incoloy MA956.

Fiber-reinforced superalloys (FRS) offer a dramatic improvement - about 100° C (180° F) or more - over current blade materials. Current FRS involve the reinforcement of iron-chromium-aluminum-yttrium (FeCrAlY) alloys with conventional tungsten lamp filaments (Alloy 218). As shown in Fig. 8, for a 35 percent fiber volume content this concept offers about a 50 percent strength improvement at 1100° C (2000° F) over a typical cast superalloy. When higher strength fibers become readily available, about a 4X improvement in density-corrected rupture strength will be possible.

Figure 9, shows that actual prototype hollow airfoils (after the JT9D first-stage turbine blade shape) with trailing edge cooling slots have been made. The airfoil section was brazed to superalloy root blocks.[14] Progress in design concepts and materials is continuing. The highly-oxidation-resistant FeCrAlY matrix adequately protects the tungsten wires from high temperature oxidation, and good thermal fatigue resistance has been documented for this composite.

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In the distant future, a ceramic (monolytnic or ceramic-fiber-reinforced) may find use in aircraft turbine blades. However, in the nearer term, silicon nitride or silicon carbide blades/rotors are being designed, fabricated (Fig. 10), and tested primarily under the AGT/CATE programs.[15] A ceramic stator (such as that shown in Fig. 11) has survived 7660 km (4760 mi) of over-the-road operation in a truck engine.

Beyond these materials, improvements in turbine blade material performance can be expected either through the use of thermal barrier coatings on these advanced metallic materials or by the use of tailored components. As discussed previously, thermal barrier coatings are under development to insulate air-cooled combustors and airfoils from the high gas temperatures. In Fig. 12 at the top, one can see that for a conventionally coated superalloy, surface temperatures can reach 1000° C (1830° F) or more in a 1350° C (2460° F) gas stream. With the addition of a metallic bond coat to improve adherance and an insulative oxide overcoating, an airfoil under the same conditions might experience metal temperatures of only 900° C (1650° F).[16] The present bond coatings are generally nickel, cobalt, or iron-chromium-aluminum-based materials which provide oxidation resistance as well as a rough reactive substrate for holding on the insulative oxide. At this point in time, most effort has been focused on various zirconium oxide compositions (partially stabilized to minimize the disruptive phase transformations which occur in the pure oxide). As can be seen in the lower right of Fig. 12, both bond coat compositions and oxide stabilizer (yttrium oxide) level can have an important effect on coating life. Thus, while improvements have been made over the last several years, continued opportunities appear to exist to greatly enhance the performance of the thermal barrier coating concept.

Tailored components involve assembly of a variety of materials to concentrate those with key properties only where needed or of sub-components incorporating cooling schemes not achievable in normal cast or wrought airfoils. Here selected subcomponents are proposed to be combined to minimize/facilitate the repair of leading/trailing edge damage. Other examples of this "tailoring" approach include "wafer" airfoils and those made of various laminated or woven wire materials. The latter design/fabrication concepts are aimed at increasing air cooling efficiency to allow cooling flow reductions and engine performance improvements.

Figure 13 gives one view of the eventual possibilities of combining several high performance materials into a tailored airfoil. Such a concept can exploit the best materials for each critical region by using high strength alloys in the root and spar and highly environmentally-resistant and, low-cycle-fatigue (LCF) resistant alloys at the airfoil edges and tip. This concept also offers the potential of reduced consumption of strategic elements.

Turbine Disk Materials

Strength trends in turbine disks are shown in Fig. 14. In the past, improvements in conventionally cast and wrought disk materials were made primarily by compositional modifications to add strengthening elements. Since disks require high strength but operate at only moderate temperatures (about 650° C (1200° F), powder metallurgical processes have been introduced

into disk fabrication to improve disk homogenity, as well as to allow use of even higher strength materials. However, as can be noted in this figure, the projected improvements in disk strength are not expected to be great in the late 1980's and 1990's. For that reason, new disk design/fabrication concepts will be required to meet the higher performance requirements anticipated for future gas turbine engines.

Figure 15 reflects the progress that has been made in the area of powder metallurgical fabrication of disks. Here Low Carbon Astroloy was HIP (Hot Isostatic Press) formed to a disk shape. Note that "hipping" saves approximately 45 kg (100 pounds) of input material as compared to the conventional forging process.[17] Also note that such disks are quite heavy and thus are presently major consumers of critical materials.

Figure 16 presents one possible concept to enhance the properties of disks for advanced gas turbine service. By initially filling the rim area of a powder metallurgy disk "can" with a creep resistant material and subsequently filling the bore area with a different but low-cycle-fatigue resistant material, it is also possible to tailor the components' properties for the particular requirements involved. This concept builds on the powder metallurgy disk technology which has been shown to save material, and it conceptually offers a means of concentrating the strategic alloying elements at the rim where they are most needed. This approach could also aid in conserving the use of these elements in the lower temperature regions where alternative materials might well be employed.

The Future

The purpose of this paper was to overview the trends in high temperature materials development for gas turbine engines. Three areas were briefly discussed: combustor materials, turbine airfoil materials, and turbine disk materials. In the area of combustors it appears that the use of oxide dispersion-strengthened alloy segments on a more-conventional superalloy structure and transpiration-cooled materials offer two ways to reduce cooling and extend combustor operating temperatures. Further enhancement can be expected by the coating of the hot walls with improved thermal barrier coatings. In the automotive area, ceramics such as alpha silicon carbide appear to offer low cost/high temperature potential for combustor usage.

In regard to airfoil materials, one can expect that improvements will continue in the area of single crystal turbine blades and vanes primarily via modification of alloy compositions. It is also possible that combinations of materials will be assembled into tailored components to offer a way to optimize properties or cooling at critical locations on an airfoil. Beyond that, one can expect a growing interest in the ODS superalloys and in fiber-reinforced superalloys whereby the oxidation resistant matrix fully protects the high strength tungsten fibers from the environment. Such fiber reinforcement may one day be coupled with a ceramic matrix as well. Continued improvement in thermal barrier coatings will, in general, also further enhance the opportunities for higher engine operating temperatures. And if technical progress in ceramics continues at its present rate in support of automotive applications, it can be expected that some of the improved materials will become ready for consideration in utility/industrial

turbines in the not-too-distant future. (Aside from ceramic turbine shrouds and thermal-barrier coatings, it is not expected that ceramics will be considered for man-rated aircraft engine service in the near future).

Finally, in the area of turbine disks, one can anticipate continued development and exploitation of the dual alloy concept via powder metallurgy or alternative approaches. This concept offers the ability to concentrate the key critical elements and high strength materials where they are most needed.

One can see that these views of the future for gas turbine components involve a multiplicity of materials, processes, and designs. We believe that multiple materials systems, comprised of a number of materials and coatings each providing a key property, will become the rule rather the exception. While such a future would hold great promise for improved gas turbine performance and component lives, the increases in component cost and complexity could be significant. For this reason, one might also expect continued growth of advanced materials processing technology to accompany the already significant activities in advanced materials development. Higher materials complexity will also require advances in the processes needed to repair and refurbish these materials periodically during their service life. And, such complexity can also be expected to require improved nondestructive evaluation (NDE) methods to assure quality control during manufacture and during service.

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TABLE I. - TURBINE OPERATING PARAMETERS

	Maximum	Gas temp.	Approximate Life, hr	Comments
Advanced aircraft turbofans	1340° C	(2450° F)	9 000	Clean fuel, ppm S HP turbines ~50 HP/Lb
Space shuttle turbopumps	690	(1270)	10	High pressure H_2 + steam, >100 HP/Lb
Pressurized-fluidized bed turbocompressors	950	(1700)	50 000	High Na, K, erosion, fouling
Advanced electric utility turbines	1550	(2820)	50 000	High S, V, fouling multifuel
Automotive turbines	1290	(2350)	3 500	Very low cost, road dust, salt, multifuel

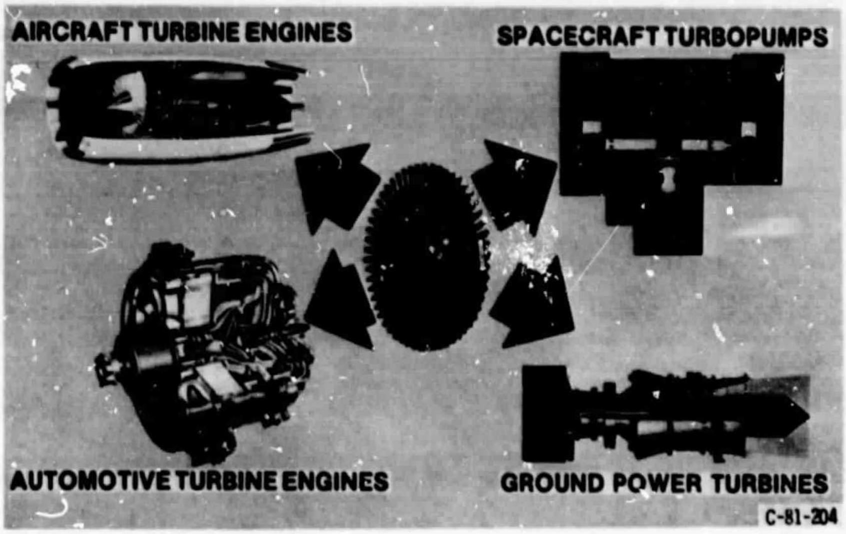

Figure 1. - Uses of high-temperature turbine materials.

PAST	CURRENT
STAINLESS STEEL SHEET OR NICKEL-BASE ALLOY SHEET	NICKEL-BASE ALLOY SHEET OR COBALT-BASE ALLOY SHEET PLUS THERMAL BARRIER COATINGS

FUTURE?

OXIDE DISPERSION STRENGTHENED ALLOYS
PLUS
NICKEL-BASE ALLOY SHEET
OR
IMPROVED THERMAL BARRIER COATINGS
OR
CERAMICS

Figure 2. - Combustor material trends.

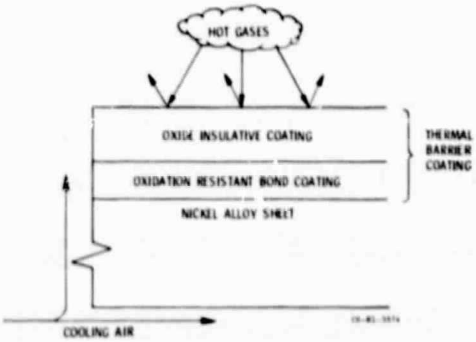

Figure 3. - Thermal barrier coatings insulate combustor walls.

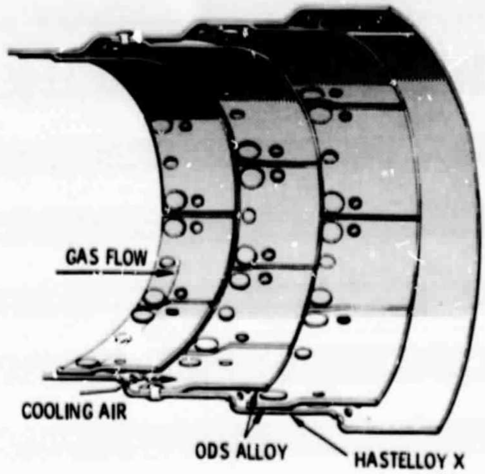

Figure 4(a). - Mechanically attached, film cooled segmented louver.

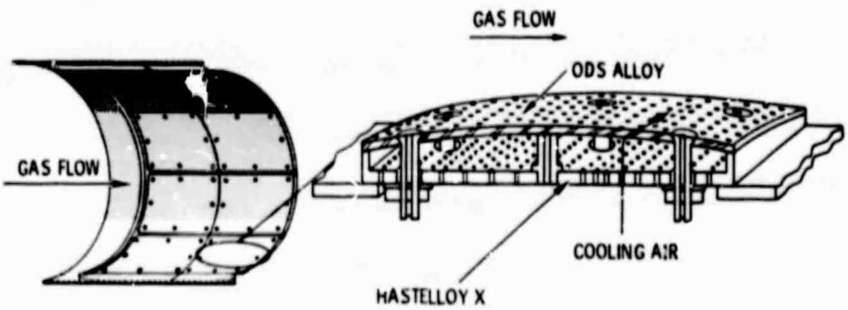

Figure 4(b). - Transpiration cooled, segmented twin-wall design.

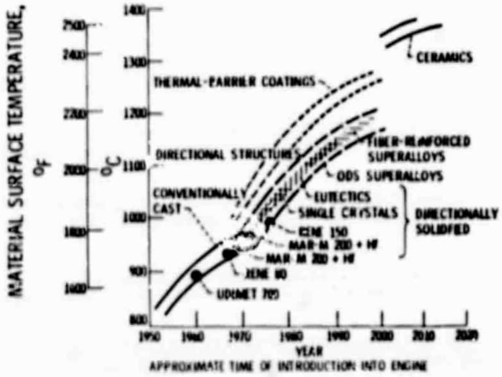

Figure 5. - Temperature capabilities of turbine blade materials.

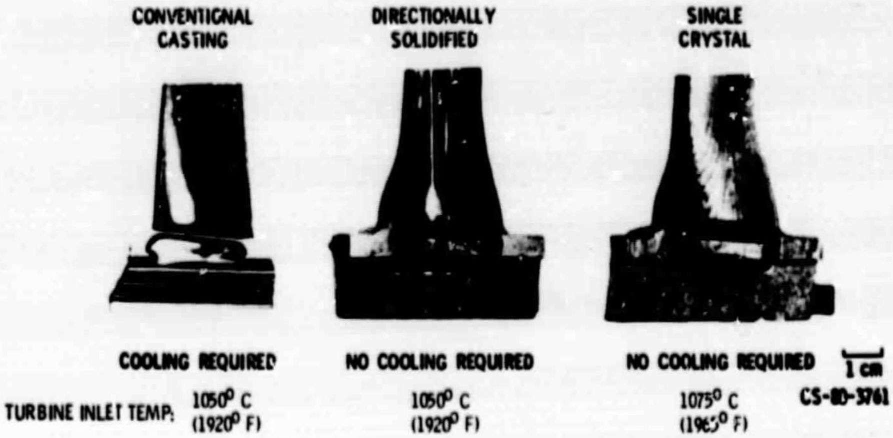

Figure 6. - Trends in cast turbine blades.

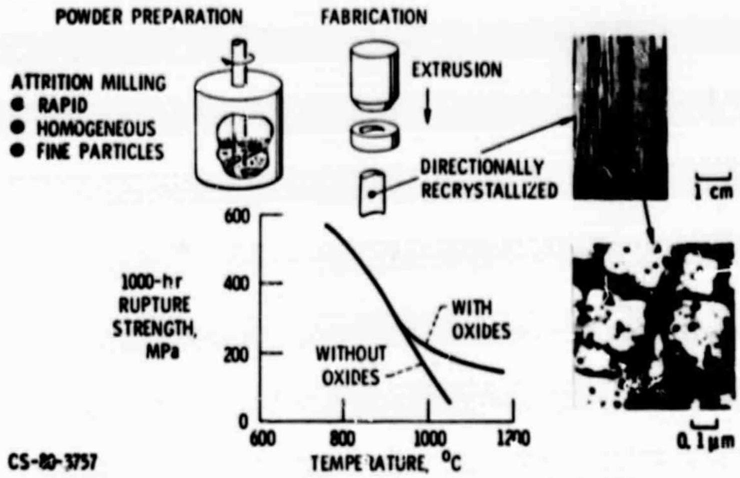

Figure 7. - Fine, dispersed oxides add high-temperature strength to alloys.

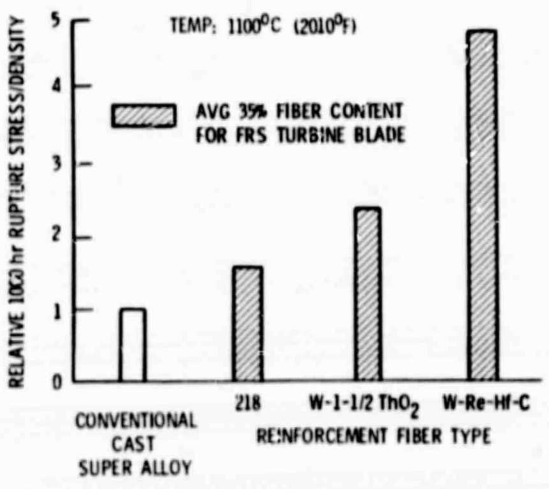

Figure 8. - Strength advantage of tungsten fiber reinforced superalloy (FRS).

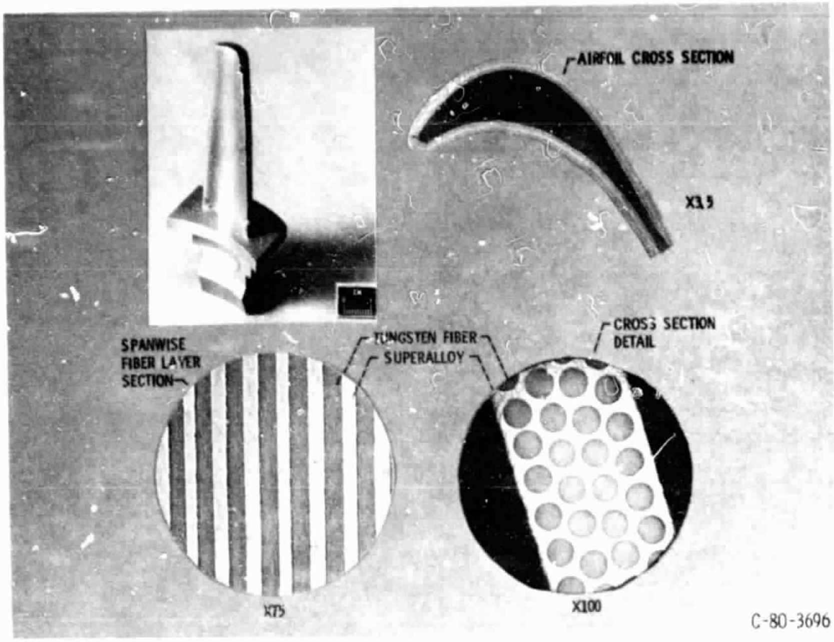

Figure 9. - Tungsten fiber/superalloy composite blade.

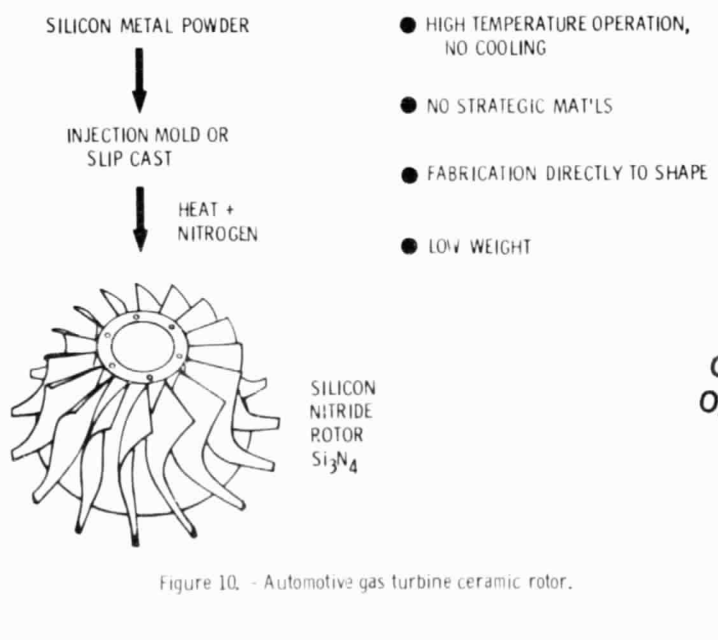

Figure 10. - Automotive gas turbine ceramic rotor.

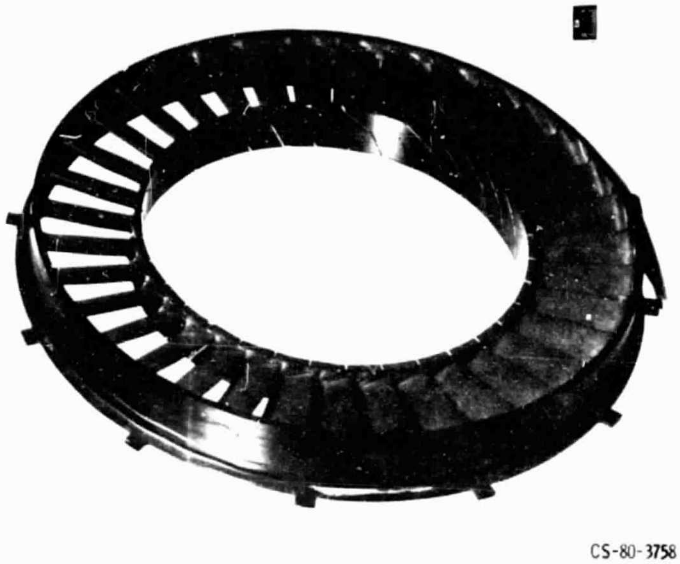

Figure 11. - Reaction-bonded silicon nitride nozzle. (25 cm outside diameter.)

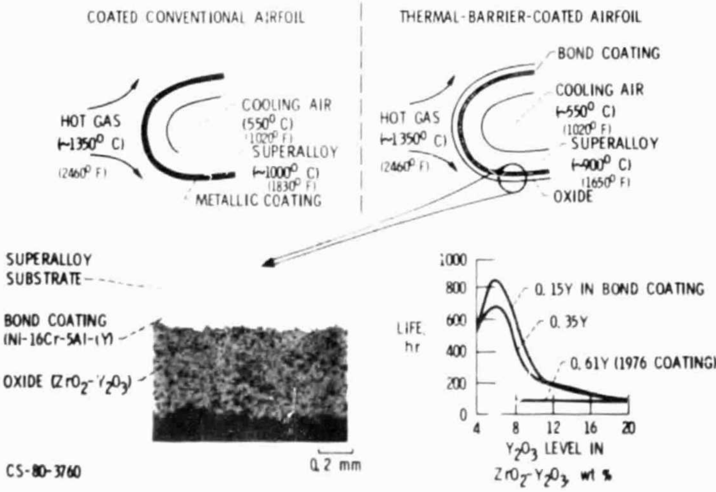

Figure 12. - Thermal-barrier coating.

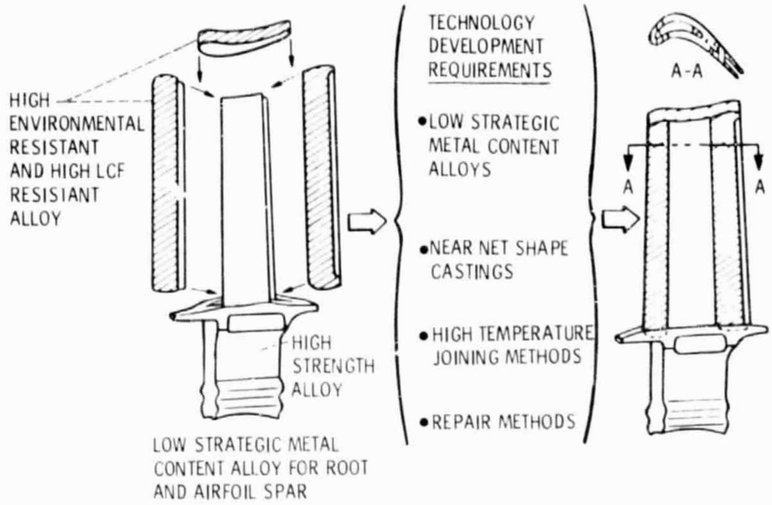

Figure 13. - Tailored fabrication as a process method to conserve strategic materials.

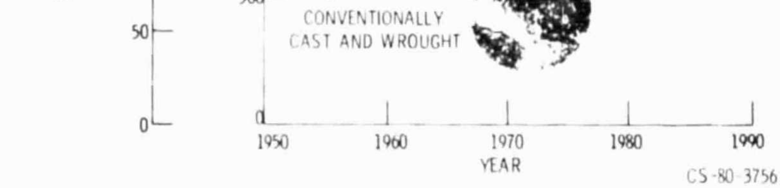

Figure 14. - Strength trends of turbine disk alloys.

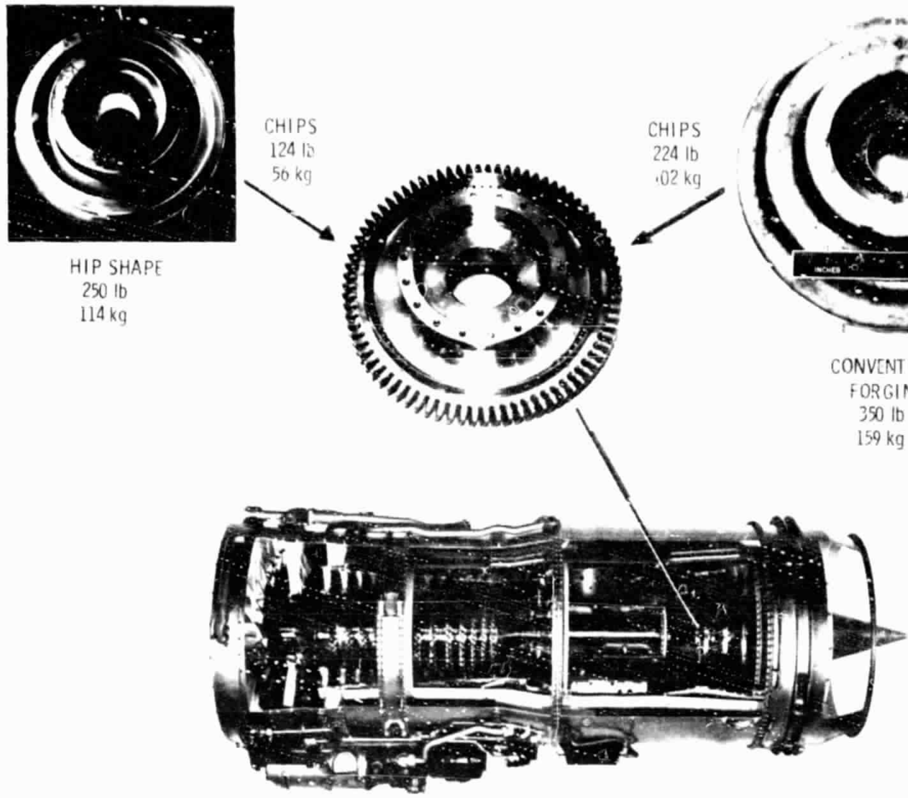

Figure 15. - Powder metallurgy reduces input material requirement.

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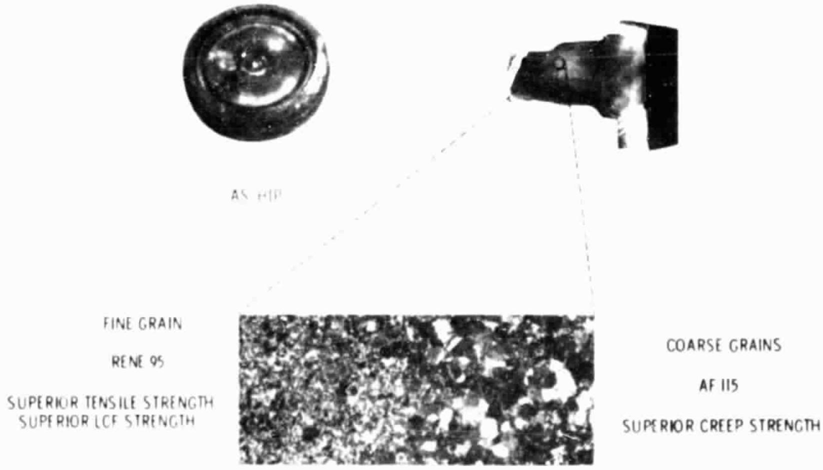

Figure 16. - Dual alloy turbine disk.